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Cook-Off Studies on the General Purpose Cast Explosives PBXC-116 and PBXC-117

by

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MAY 1976

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Naval Weapons Center

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R. G. Freeman, III, RAdm., USN . . . . Commander
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FOREWORD

This report describes an investigation, conducted during 1973 and 1974, of the cook-off hazards of explosive compositions PBXC-116 and PBXC-117. This work was sponsored by the Naval Air Systems Command under AIRTASK ~~A03P-5323/~~ ~~003C/6W4736-001.~~ A3Φ3-51ΦA/ ΦΦ8-C/3W4736-ΦΦ1*

Dr. H. J. Gryting and Dr. Russell Reed, Jr., have reviewed this report for technical accuracy.

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(U) *Cook-Off Studies on the General Purpose Cast Explosives PBXC-116 and PBXC-117* (U), by Carl M. Anderson and Jack M. Pakulak, Jr. China Lake, Calif., Naval Weapons Center, May 1976, 38 pp. (NWC TP 5629, publication UNCLASSIFIED.)

(U) This report presents the results of an investigation of the slow cook-off behavior of PBXC-116/117 explosives, and the behavior of PBXC-116/117-loaded ordnance when exposed to fuel fires. The PBXC-116/117 compositions were demonstrated to have outstanding thermal, mechanical and explosive properties.

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CONTENTS

INTRODUCTION

Two new explosive compositions, PBXC-116 and PBXC-117, specifically designed for resistance to bullet impact shock, were developed at NWC by Miss Barbara Stott under the sponsorship of the Naval Ordnance Systems Command (ORD-0332). The compositions are based on RDX suspended in an elastomeric binder, one of whose components will dissolve a small amount of the RDX. (PBXC-117 is an aluminized version of PBXC-116.) The development requirements included low cost components, processability in standard equipment, cold castability, and ambient temperature cure. All of these requirements were satisfied in the PBXC-116/117 systems.

A previous publication[1] reported the preliminary investigation of PBXC-116/117 thermal behavior. The standard, small-scale, fast cook-off procedure, as well as differential thermal and thermogravimetric analyses and differential scanning calorimeter determinations, were included in that preliminary report. These explosives demonstrated good thermal properties and, in particular, very mild reaction at a reasonably high temperature on fast cook-off. This suggested that these explosive compositions represented a breakthrough in explosive development work.

This publication is concerned with (1) the slow cook-off (SCO) behavior of PBXC-116/117, for storage life predictions, etc.; and (2) the behavior of PBXC-116/117-loaded ordnance when exposed to fuel fires. The reactions to fast and slow fire heating were mild, deflagrations only, under conditions that produced explosions and detonations with Tritonal and Composition B loads.

These compositions have been interim qualified for general purpose main charge applications and have shown "*outstanding superiority over conventional explosives in their resistance to inadvertent initiation by high velocity projectiles and fuel fires.*"[2]

[1]Naval Weapons Center. *Thermal Analysis of Candidate General Purpose Cold-Cast Explosives PBXC-116 and PBXC-117*, by Carl M. Anderson and Jack M. Pakulak. China Lake, Calif., NWC, October 1974. (NWC TP 5561, publication UNCLASSIFIED.)

[2]Naval Ordnance Systems Command. *Interim Qualification of PBX-226(1) Explosive Composition*. Washington, D.C., NAVORD-0322A, 9 and 11 April 1974. (NAVORDNOTICE 80[illegible], publication UNCLASSIFIED.)

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EXPERIMENTAL

Slow cook-off involves the determination of the time required for a sample, held at a given temperature, to self-destruct. Samples in three sizes at three temperatures are required for analysis of the data.

The samples were cast in waxed paper cartons with a bead thermocouple in the exact center of the billets. In the largest size, a second thermocouple was located at a one-half radius point. The samples were prepared for cook-off by wrapping first with one layer of 0.0005-inch thick aluminum foil, then with two layers of 0.002-inch thick aluminum foil. A tab thermocouple, in which the thermocouple wires are individually spot welded to a 1 cm^2 stainless steel tab, was placed on the surface under the thin aluminum foil and covered with the outer foils. The air oven consisted of a large aluminum tube (10-inch diameter by 4-foot long, with electric surface heaters attached to the outer wall) suspended in a transite box filled with rock wool. The oven temperature was controlled, via a thermocouple imbedded in the outer surface of the aluminum tube, with a Honeywell recorder-controller. By this means, the air temperature variation in the oven, with the fiberglass cloth end-plugs in place, was held at less than ±3°C. Thermocouple time-temperature data were recorded on stripchart recorders. Table 1 lists the cook-off determinations made on the three sizes in the two systems.

Warhead cook-off experiments in aircraft fuel fires were run using the following procedure. The warhead, with thermocouples appropriately installed in and on the unit, was suspended from an A-frame approximately 3 feet above a 24-foot diameter shallow pit containing JP-5 fuel. The chain hangers and the thermocouple leads were thoroughly insulated. This was done to minimize extraneous heat paths into the warhead and to prevent burning off of the thermcouple leads leaving the lines reporting flame temperatures. The pit was filled with sufficient JP-5 fuel (800-1,000 gallons) for a 17-20 minute fire. This was covered with 10-15 gallons of gasoline, to ensure ignition, and then ignited using 4-6 electric matches wrapped with gasoline soaked rags. Time to reaction was taken as time from firing the matches. Usually, 15-45 seconds were required to establish the flame over the entire surface of the fuel. Time-temperature data were recorded via a "*data logger*" magnetic tape system for later reduction and plotting by available computer programs. Photographic and video tape records were made of visual effects. Audible effects were monitored on a sound system and recorded on the video tape.

TABLE 1. PBXC-116/117 Cook-off Determinations.

SCO run no.	Size, inch		Weight, grams	Air in oven temperature, °C	NWC site
	Diam.	Nominal length			
PBXC-116					
107	1¼	3½	133	177	65-B
109	1¼	3½	132	151	65-B
115	1¼	3	134	164	65-B
111	3¼	6	1,430	137	65-B
123	3¼	6	1,495	154	67-A
127	3¼	6	1,470	147	67-A
129	3¼	6	1,500	157	67-A
113	5	5½	2,900	151	203-B
117	5	5½	2,860	141	203-B
119	5	5½	2,950	130	203-B
PBXC-117					
108	1¼	3½	139	177	65-B
110	1¼	3½	134	150	65-B
116	1¼	3	133	162	65-B
112	3¼	6	1,500	137	65-B
124	3¼	6	1,506	151	67-A
128	3¼	6	1,502	147	67-A
130	3¼	6	1,490	158	67-A
114	5	5½	2,990	150	203-B
118	5	5½	2,950	141	203-B
120	5	5½	3,200	131	203-B

TREATMENT OF EXPERIMENTAL DATA

Slow cook-off time-temperature records provide the raw data from which thermal properties, an estimation of storage life times, and a prediction of time-to-cook-off in other sizes and at other temperatures can be obtained.

THERMAL PROPERTIES

The time-temperature data recorded during the warm-up period are used to evaluate the thermal diffusivity (α) of the material. An equation derived by Cadoff and Miller[3] was used for this cylindrical case

[3]Cadoff, Irving B. and Edward Miller. *Thermoelectric Materials and Devices*. New York. Reinhold Publishing Corp., 1960. pp. 124-132.

$$\Delta T = \frac{a^2}{4\alpha}\frac{dT}{dt} \tag{1}$$

Where ΔT is the difference in temperature between the outside surface and the center of a cylinder of radius (a) and a heating rate of dT/dt on the outside surface. The thermal diffusivity, α, is related to the thermal time constant of the material (τ), defined as

$$\tau = \frac{a^2}{\alpha} \tag{2}$$

and to the thermal conductivity (λ) by the relation $\lambda = \rho c \alpha$. Where ρ is the density and c the specific heat of the material.

In the slow cook-off procedure, the cold samples are introduced into a preheated oven which is immediately closed. The sample temperature rises exponentially to the oven temperature and above. The Arrhenius chemical reaction rate equation

$$k = A\ exp(-E^*/RT) \tag{3}$$

and the zero order rate equation

$$dc/dt = k \tag{4}$$

are combined to calculate an amount of reaction occurring during the warmup period. In the form of the fraction of the sample reacted (f) the integrated rate equation combined with the Arrhenius equation produces the equation needed:

$$f = t\ A\ exp(-E^*/RT) \tag{5}$$

where f is the fraction reacted in the time interval, t, for a reaction whose activation energy is E^* and frequency factor is A. An approximation for time zero is obtained from the time-temperature records by taking the sum of the fractions reacted in each of five 10°C intervals before the "*cross-over*" point and then calculating the time at the oven temperature for that amount of reaction to occur. The cross-over point, usually at or near the oven temperature, represents the temperature and the time at which the temperature at the center of the sample goes above the temperature at the surface of the sample. This computation is carried out for the sample surface temperatures and for the sample center temperatures, and a simple average of the two times is used as time zero (t_0). A program, stored on a magnetic card, for the Hewlett-Packard Model 9820 calculator has been written to make this computation. The program, and the computation procedure, is given in Appendix A.

Zinn and Mader[4] in their computations from thermal explosion theory and heat flows in an explosive sample, present a characteristic term that they call a "*critical temperature*". This critical temperature is defined as the temperature at which the heat produced by chemical reactions in the sample is just balanced by heat exchanges from the sample. That is, the temperature of the surroundings at which the temperature distribution in the sample is uniform. This characteristic critical temperature can be considered as a point above which the sample will certainly cook-off and below which the sample may cook-off given sufficient time. This characteristic critical temperature is defined by the equation:

$$T_m = \frac{E^*}{2.303R \; log\left(\dfrac{a^2 \; AQE\rho}{\lambda R T_m^2 \delta}\right)} \tag{6}$$

where T_m = characteristic critical temperature, °K
a = one-half thickness or radius, cm
Q = heat of reaction, cal/g
ρ = density, g/cm^3
λ = thermal conductivity, cal/cm · °K
R = universal gas constant, 1.987 cal/mole–°K
δ = a shape factor

The shape factor, δ, takes on the value of 1.00 for an infinite slab of thickness 2a; 2 for an infinite cylinder of radius a; 2.76 for an equi-cylinder (diameter and height = 2a; and 3 for a sphere with radius a. Using data from the previous report in this series (see footnote 2) and the thermal diffusivity measured here, an iteration on T_m in Eq. (6) converges rapidly to a value for T_m. Data used for the iteration are listed in Table 2. A program was written for this iteration, for use with the Hewlett-Packard Model 9820 calculator, and is provided in Appendix B.

TABLE 2. Data for Equation (6).

Term	PBXC-116	PBXC-117
E*,kcal/mole	45.0	45.0
A, sec^{-1}	1.4×10^{17}	2.6×10^{17}
Q, cal/gram	500	520
ρ, gram/cm^3	1.65	1.75
α, cm^2/sec	5×10^{-4}	8×10^{-4}
c, cal/gram-°K	0.33[a]	0.30[a]
λ, cal/cm-sec-°K	2.7×10^{-4}	4.2×10^{-4}
δ	2.76	2.76

[a]Estimated values from other castable PBX/RDX systems.

[4]Zinn and Mader, *J. of Applied Physics*, 31:323, 1960.

Zinn and Rogers[5] using the approach described by Zinn and Moder (see footnote 4), developed an empirical relation, Eq. (7), from experimental cook-off results of a series of pure explosives. This relation gives a useful prediction of time to cook-off, t_c, using the activation energy, E^*, and the thermal time constant, τ, defined in Eq. (2):

$$\log \frac{t_c}{\tau} = f\left[E^*\left(\frac{1}{T_m} - \frac{1}{T_1}\right)\right] \tag{7}$$

Zinn and Rogers published a curve defining the function which then provides a means of determining the characteristic "*critical temperature*", T_m, from experimental cook-off data. From a plot of experimental time-to-cook-off, t_c, versus the reciprocal of the absolute oven temperature, T_1, and the value of the function in Eq. (7) (equal to 1.6 for an infinite cylinder at the point where $t_c = \tau$), the characteristic critical temperature is calculated from

$$\frac{1}{T_m} = \frac{1}{T_1} - \frac{1.6}{E^*} \tag{8}$$

With a value for the characteristic critical temperature available from thermal explosion theory, Eq. (6), or from experimental data, Eq. (8), predictions can be made of time-to-cook-off at other sizes and temperatures. Predictions are quite good for values of t_c/τ less than about 10^3 for non-metallized explosives and propellants. For metallized systems, the method is not as well defined but is useful for order of magnitude predictions of time to cook-off.

RESULTS

PBXC-116

Cook-off determinations, as indicated in Table 1, were run on three sample sizes and at three temperatures. Reproductions of typical time-temperature runs are presented in Figures 1 through 3. Data from these runs are summarized in Table 3 and in Figure 4 as a plot of equivalent time to cook-off versus the reciprocal of the oven temperature in degrees Kelvin (columns 6 and 7 in Table 3).

[5] Zinn and Rogers. *J. of Physical Chemistry*, 66:2646, 1962.

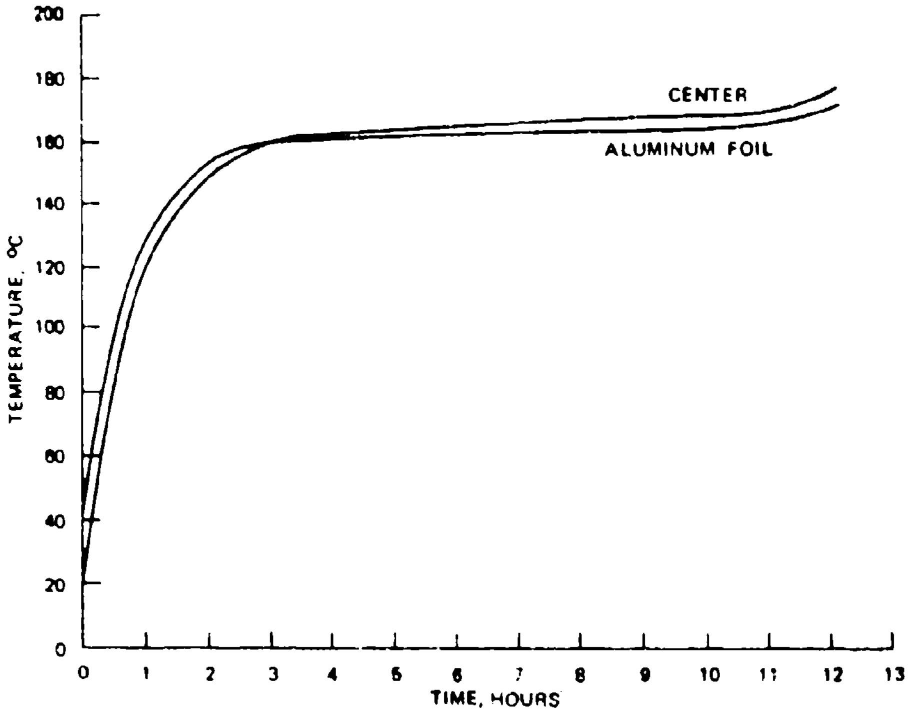

FIGURE 1. Time-Temperature Data, PBXC-116 (SCO-115, 1¾-inch-diameter by 3-inch-long sample size).

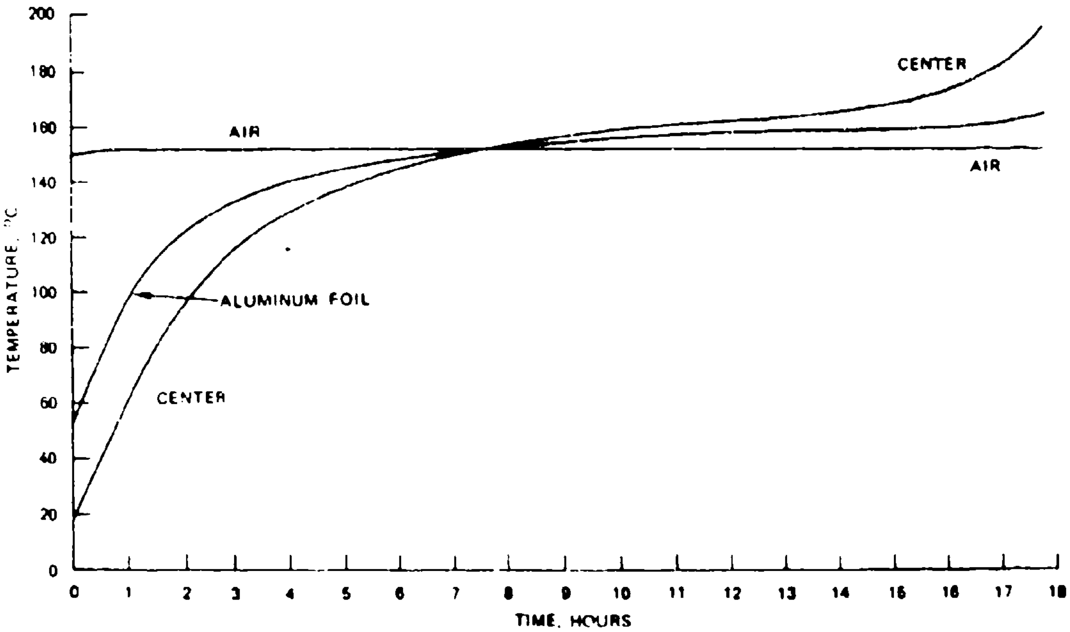

FIGURE 2. Time-Temperature Data, PBXC-116 (SCO-123, 3¼-inch-diameter by 6-inch-long sample size).

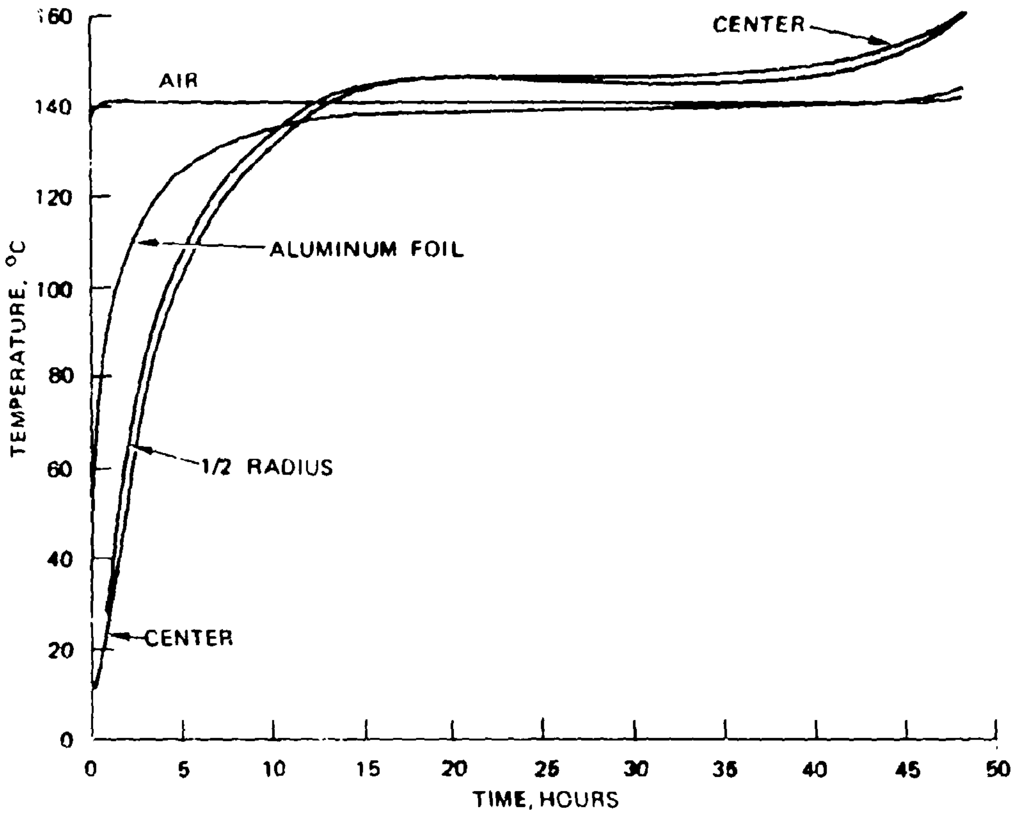

FIGURE 3. Time-Temperature Data, PBXC-116 (SCO-116, 5-inch-diameter by 5½-inch-long sample size).

TABLE 3. PBXC-116 Cook-off Data.

SCO run no.	Size, inch		Cross-over temperature, °C	Equivalent time in oven,		Time at T_I seconds	$10^3 \times 1/T_I$
	Diam.	Length		hours	minutes		
107	1¼	3½	176	2	45	3.0×10^3	2.226
109	1¼	3½	151	66	50	2.32×10^5	2.357
115	1¼	3½	162	12	9	3.47×10^4	2.298
111	3¼	6	136	153	29	5.3×10^5	2.444
123	3¼	6	152	17	38	4.2×10^4	2.352
127	3¼	6	147	24	18	6.6×10^4	2.380
129	3¼	6	159	9	20	1.16×10^4	2.314
113	5	5½	156	12	56	1.33×10^4	2.330
117	5	5½	137	48	22	1.41×10^5	2.438
119	5	5½	129	194	54	6.6×10^5	2.486

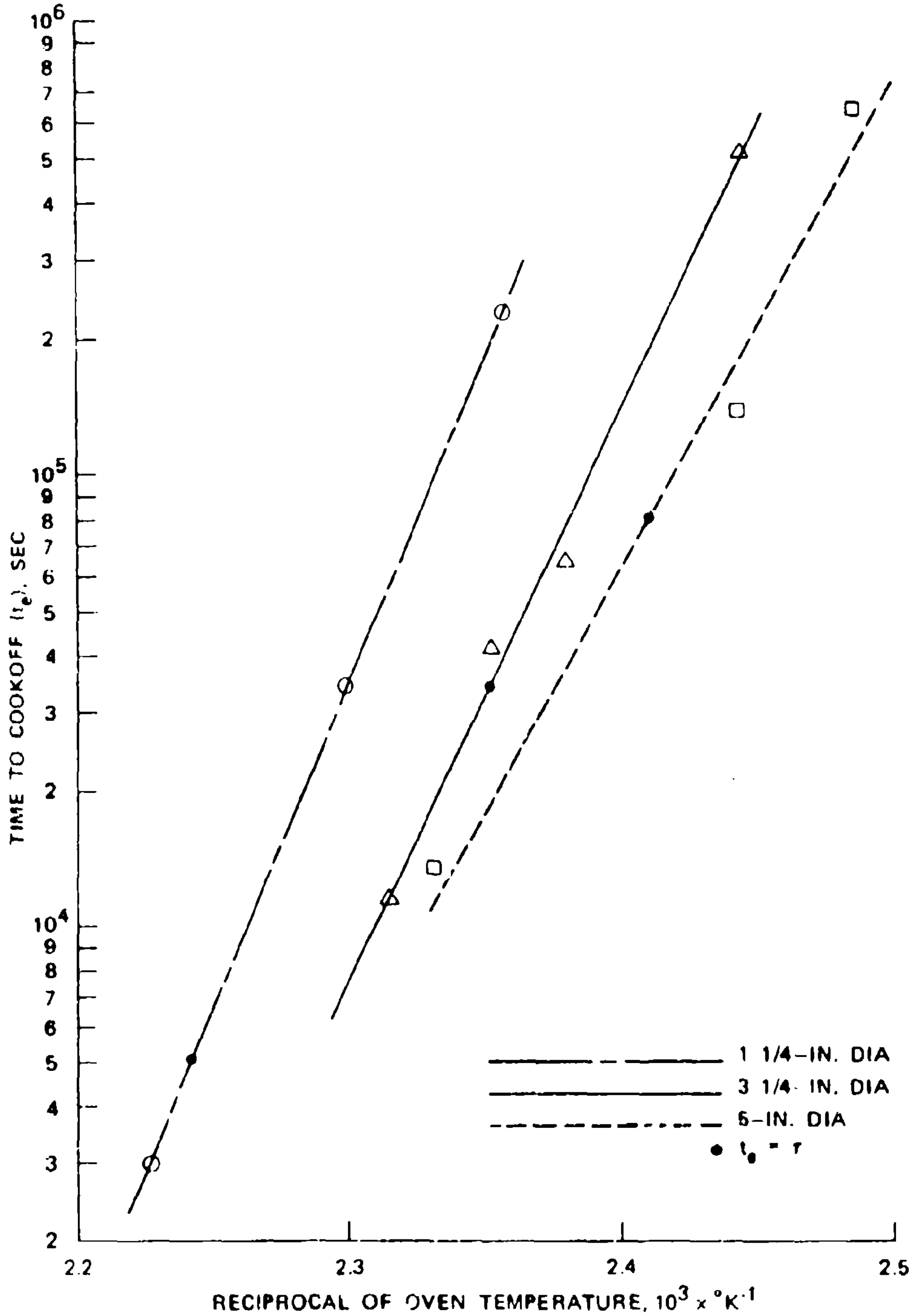

FIGURE 4. Equivalent Time to Cook-Off Versus Oven Temperature (PBXC-116).

PBXC-117

Cook-off determinations for PBXC-117 were run using a series of sample sizes and temperatures. Reproductions of typical time-temperature data are shown in Figures 5 through 7. Table 4 is a summary of the data from these runs. A graphical summary is given in Figure 8 as a plot of equivalent time to cook-off, t_c, versus the reciprocal of the oven temperature in degrees Kelvin (columns 6 and 7 in Table 4) at the various sizes.

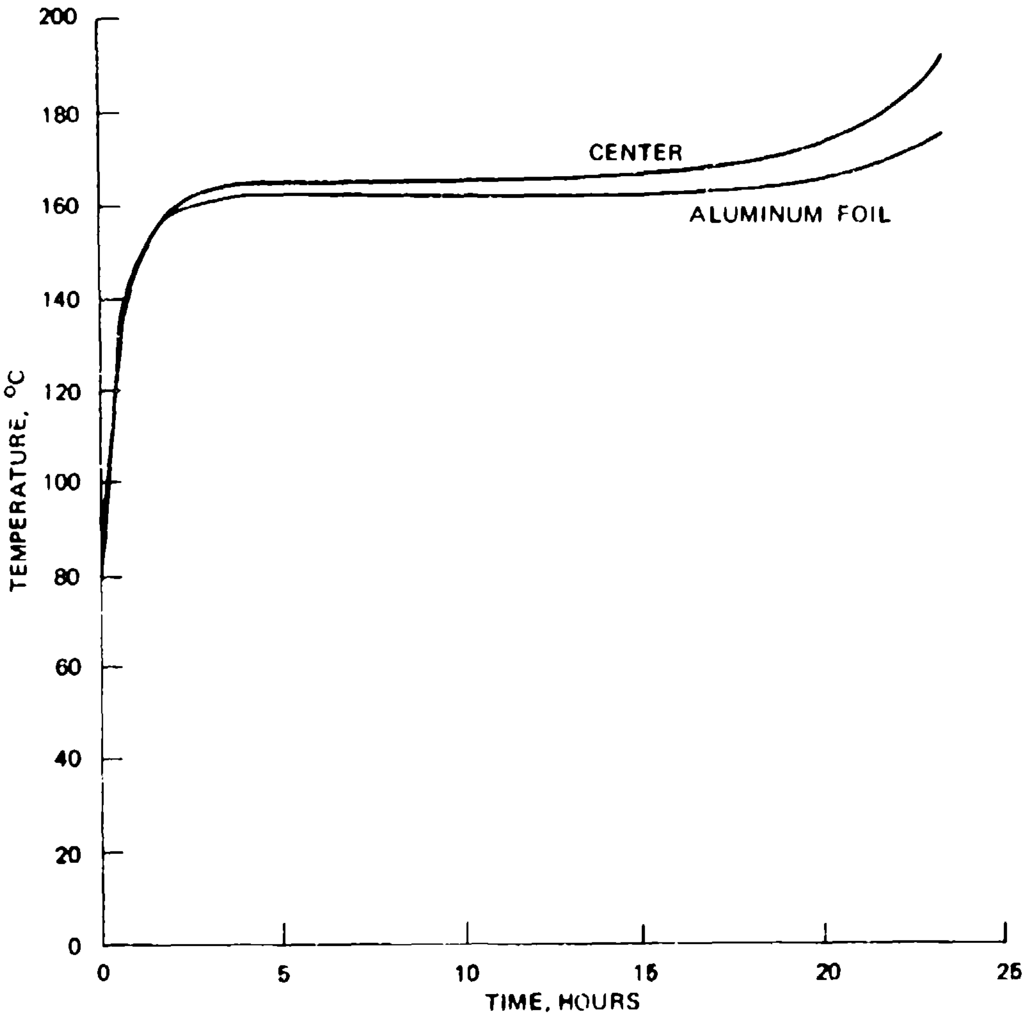

FIGURE 5. Time-Temperature Data, PBXC-117 (SCO-116, 1¼-inch-diameter by 3-inch-long sample size).

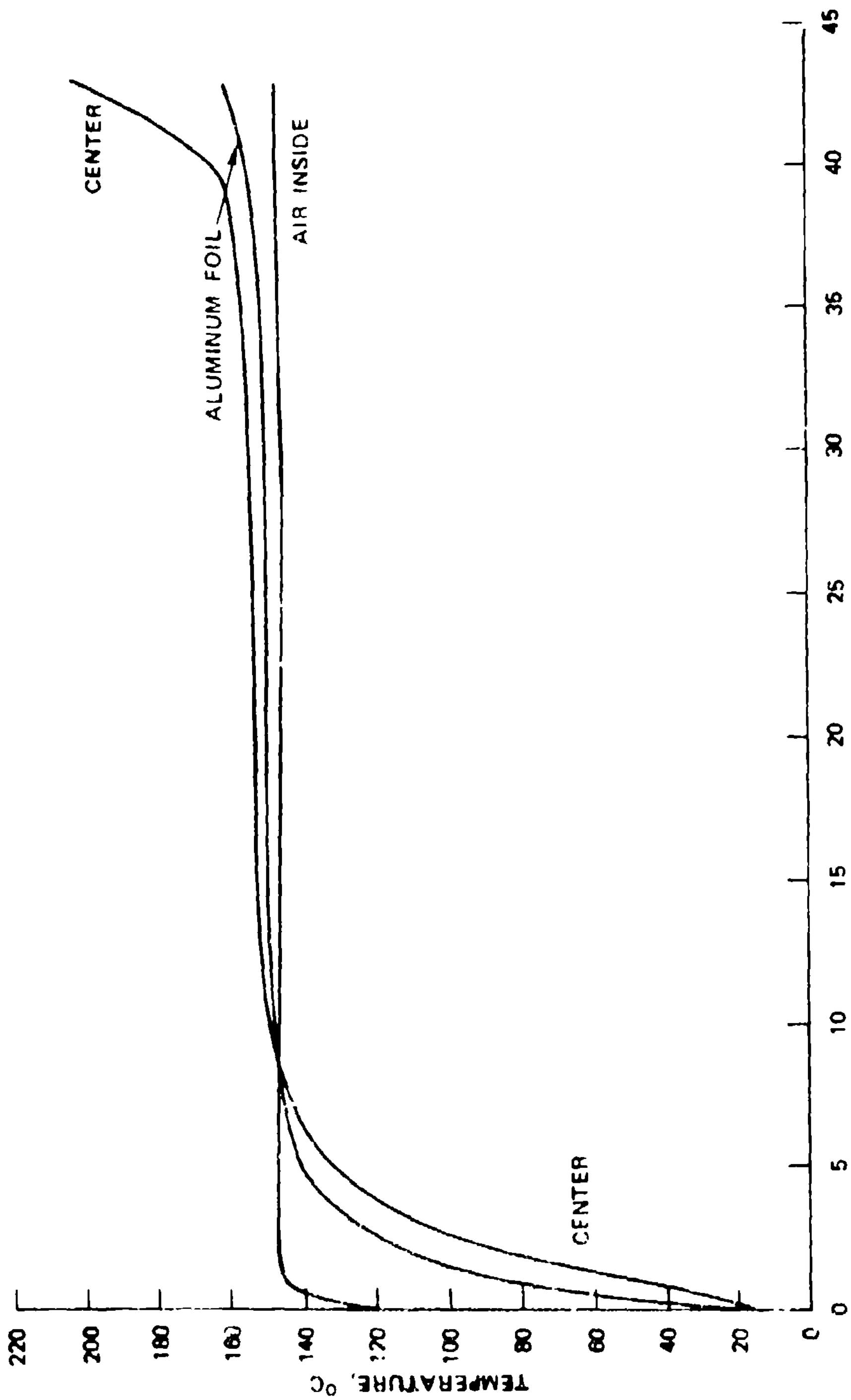

FIGURE 6. Time-Temperature Data, PBXC-117 (SCO-128, 3¾-inch-diameter by 6-inch-long sample size).

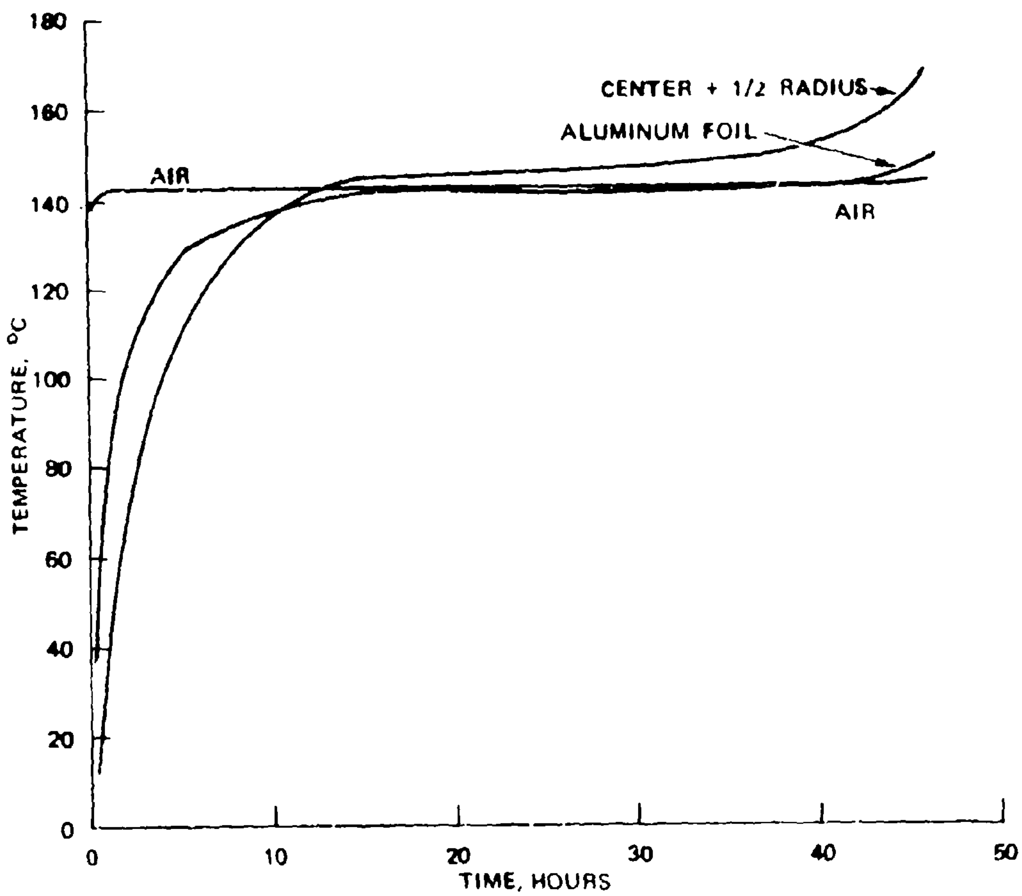

FIGURE 7. Time-Temperature Data, PBXC-117 (SCO-118, 5-inch-diameter by 5½-inch-long sample size).

TABLE 4. PBXC-117 Cook-off Data.

SCO run no.	Size in. Diam.	Size in. Length	"Crossover" temperature °C	Equiv. time in oven, Hours	Equiv. time in oven, Minutes	Equiv. time at T_1,sec	$10^3 \times 1/T_1$
108	1¼	3½	171	3	16	5.76×10^3	2.251
110	1¼	3½	149	89	10	3.15×10^5	2.369
116	1¼	3½	160	23	0	7.56×10^4	2.308
112	3¾	6	138	219	2	7.57×10^5	2.432
124	3¼	6	154	Recorder failed			
128	3¾	6	147	43	20	1.33×10^5	2.380
130	3¾	6	157	10	32	1.82×10^4	2.324
114	5	5½	144	23	10	5.80×10^4	2.397
118	5	5½	136	81	5	$2.64 \times 10^{[illegible]}$	2.444
120	5	5½	130	297	20	1.035×10^6	2.480

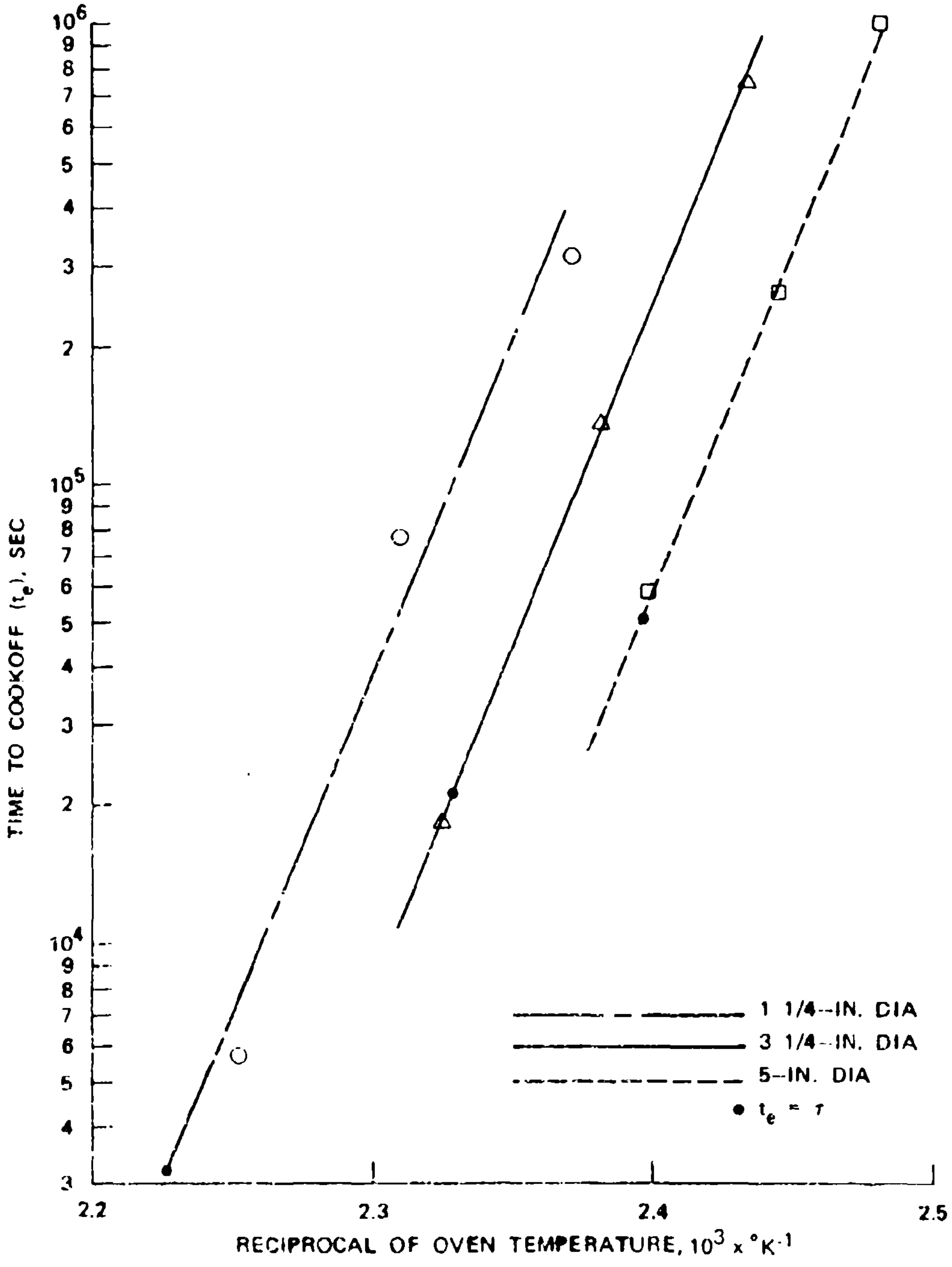

FIGURE 8. Equivalent Time to Cook-Off Versus Oven Temperature (PBXC-117).

DERIVED DATA

Characteristic "*critical temperatures*" for these systems are given in Table 5 for the sizes considered here as calculated from thermal explosion theory, Eq. (6), and as calculated from the experimental data using Tables 3 and 5 and Eq. (8). These numbers provide the basis for predicting time to cook-off in other sizes and at other temperatures. The data in Table 5 are plotted in Figure 9 as log radius versus $1/T_m$. The constants for the least squares straight line for each series of points are appended to Table 5. The constants are for a line in the form of

$$\log a = A + B/(T_m + 273.2) \qquad (9)$$

where a is the radius in centimeters, of the cylinder being considered.

TABLE 5. Characteristic Temperatures for PBXC-116 and PBXC-117.

Diam., inch	PBXC-116			PBXC-117			RDX	
	τ, sec	Theory, °C	Experimental, °C	τ, sec	Theory, °C	Experimental, °C	τ, sec	Theory, °C
1¼	5.10×10^3	161	166	3.16×10^3	158	169	3.25×10^3	156
3¼	3.44×10^4	145	146	2.13×10^4	142	150	2.19×10^4	142
5	8.1×10^4	138	135	5.04×10^4	136	138	5.18×10^4	135
A		10.55	7.79		-10.89	7.83		-11.57
B		4,669	3,513		4,781	3,558		5,056

As an example of the use of these numbers, consider a Mk 81 general purpose bomb loaded with PBXC-116. In the Mk 81, the explosive charge has a diameter of about 8.2 inches, or radius $a = 10.41$ *cm*. Reading from Figure 9, or calculating from the line in Eq. (9), T_m is equal to 130°C (explosion theory) or 126°C (experimental cook-off data). The thermal time constant, τ for this size is 2.17×10^5 seconds. Now, for a 500-hour cook-off, $t_c = 1.80 \times 10^6$ seconds, $t_c/\tau = 8.3$, and $\log (t_c/\tau) = 0.92$. This gives a value of the function in Eq. (7) of 0.35 from the Zinn and Rogers curve (see footnote 6). Using an activation energy of 45 kcal/mole, the oven temperature needed is $T_1 = 129$°C (264°F) from thermal explosion theory or 125°C (257°F) from experimental cook-off data.

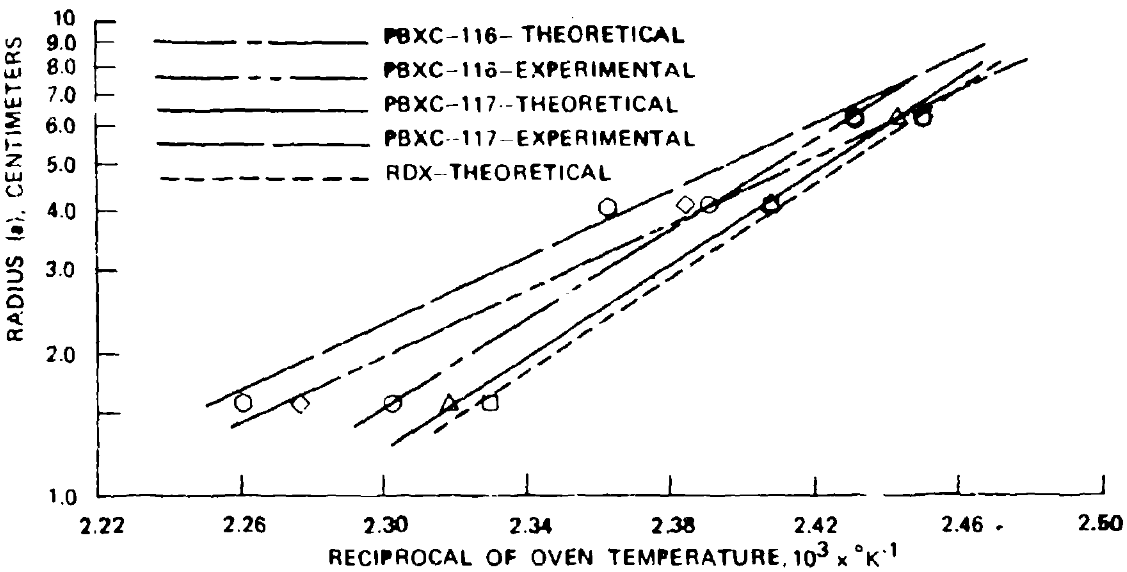

FIGURE 9. Sample Size Versus Characteristic Temperature.

As another application, a calculation was made of the radius required to satisfy Eq. (6) at assorted characteristic critical temperatures (Figure 10). A similar computation for pure RDX is also included in Figure 10. These lines represent the radii of the maximum size of cylinder that will not self-heat at that temperature. At temperatures above the lines or for sizes larger than the lines, the sample will eventually cook-off. Cook-off could still occur at smaller sizes and lower temperatures. but at much longer times. Of interest here is the fact that the binder system in PBXC-116/117 has so little effect on the RDX.

ZUNI WARHEAD COOK-OFF TESTS

The exemplary behavior of these explosive systems in the 2-pound, small cook-off bombs, as reported in the preliminary thermal study (see footnote 2), indicated that PBXC-116/117 should be useful general purpose explosives. A brief investigation was made to demonstrate the behavior of these explosive systems in two typical rocket warheads in a fuel fire. The Mk 24 and Mk 63 Zuni warheads were chosen because they are high-use, readily available items. The Mk 24, in particular, was used because the steel wall thickness (0.4-inch) relates directly to the general purpose series bombs and represents a heavy confinement.

The experimental procedure, standardized at NWC, involved suspending the ordnance item over a 24-foot octagonal pit with sufficient JP-5 fuel to produce a fire for a predetermined length of time. The JP-5 fuel was covered with a few gallons of gasoline, to ensure ignition, and ignited with electric matches. The ordnance item was fitted with thermocouples at strategic points and thermocouple output was recorded on a digital tape "*data logger*" system. Reduction to time-temperature and plotting was done on an IBM 1104 computer.

Test SCO-125

A 5-inch, Mk 24 Zuni warhead, with the regulation black cavity paint removed and instrumented with two thermocouples (TC-1 and TC-2) attached to the inside skin, was given a wash-coat of diluted PBXC-117 binder and loaded with PBXC-117 explosive. Neither fuze nor booster was installed. Two additional thermocouples (TC-3 and TC-4) were placed (in air) at about 10 centimeters from each side of the warhead to read the flame temperature. Time zero was calculated as the time the electric matches were ignited to start the flame. The entire pit was aflame at 12 seconds and the external flame temperature thermocouples passed 538°C (1000°F) at 45 seconds.

Figure 11 is a photograph of the installation showing the warhead suspended about 36 inches above the fire pit. The thermocouple leads were carefully insulated to prevent burn-off; a burn-off can result in an open lead or in a reading of the flame temperature.

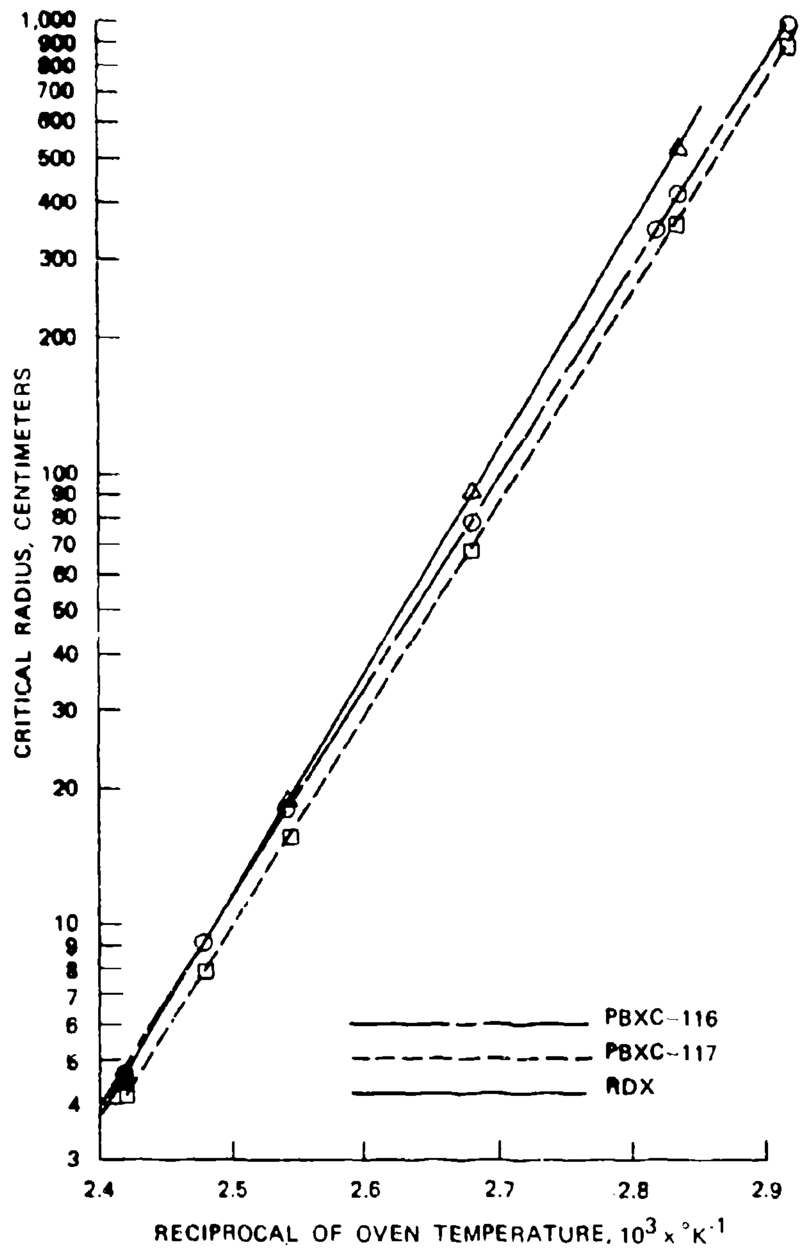

FIGURE 10. Critical Radius.

FIGURE 11. Test Setup, SCO-125. (Neg. LHL 1798-5)

A plot of the time-temperature records is given in Figure 12. The flame temperature was at the typical level, except for a long period of time to abrupt rise which may have been due to the mounting of the flame thermocouples. The film of the test shows a normal initiation with the usual 12-15 second delay to full flame.

At 105 seconds, a sharp report was heard on the audio system, but no obvious visual change in the flame was observed on the monitor or on the film. After fire burn out, the Mk 24 was still attached to the frame by the base support ring (see Figure 13). The warhead, with a 0.4-inch thick skin, had been split and laid open in what is defined as a deflagration. Figure 13 is a photograph of the warhead after the test.

Test SCO-126

A second 5-inch Mk 24 Zuni warhead was loaded with PBXC-117 and tested as in SCO-125. On this occasion, no time-temperature data were recorded due to a failure in the system. Film data were essentially the same as before with no great change in the flame as the warhead opened. The operator reported a "*heavy report*" at 75 seconds; presumably louder than the "*sharp report*" of SCO-125. Figure 14 is a photograph of the test stand after the fire had burned out showing about one-half of the case still attached to the stand. Figure 15 shows the two fragments of the warhead case, which would indicate a somewhat more enthusiastic deflagration than in the previous test.

Test SCO-128-A (ZX-4)

Four 5-inch Mk 63 Zuni warheads, each loaded with about 14 pounds of PBXC-116, were placed in a LAU-10C/A launcher with inert motors and igniters. The launcher was coated with 130 mil Pfizer Company FIREX RX2370 intumescent paint. The forward fairing was coated with TTP-0026b intumescent paint. As shown in Figure 16, the assembly was mounted three feet above the fuel in a 24-foot octagonal pit. The test was instrumented with two thermocouples on the inside shell of each warhead, one thermocouple on the forward outside skin of each warhead, one thermocouple (No. 13) on a probe inside the fairing, two thermocouples (No. 14 and 15) on the inside skin of the fairing, and four thermocouples outside the test item to read flame temperatures. Twelve-hundred gallons of JP-5 fuel were used in the fire pit. About 15 gallons of gasoline were poured onto the fuel surface to aid ignition. Time-temperature (thermocouple millivolts) data were recorded on a "*data logger*" magnetic tape system for later reduction and plotting by computer. The test was recorded on color camera film and monitored continuously with a closed circuit television and audio system.

The reduced time-temperature records for this test are given in Figure 17. Correlation of these data with the firing officer's report of the test events is difficult

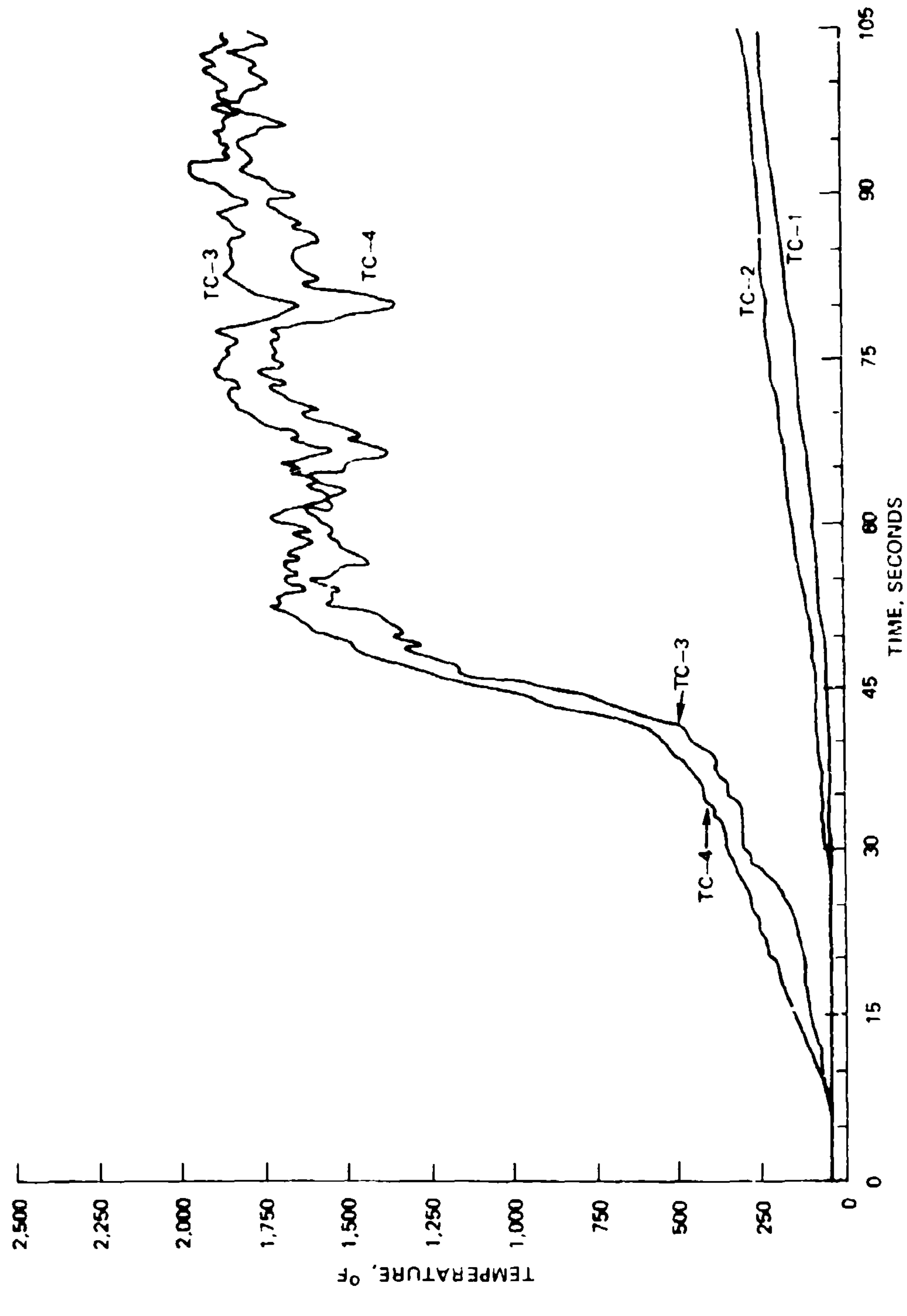

FIGURE 12. Time-Temperature Data, SCO-125.

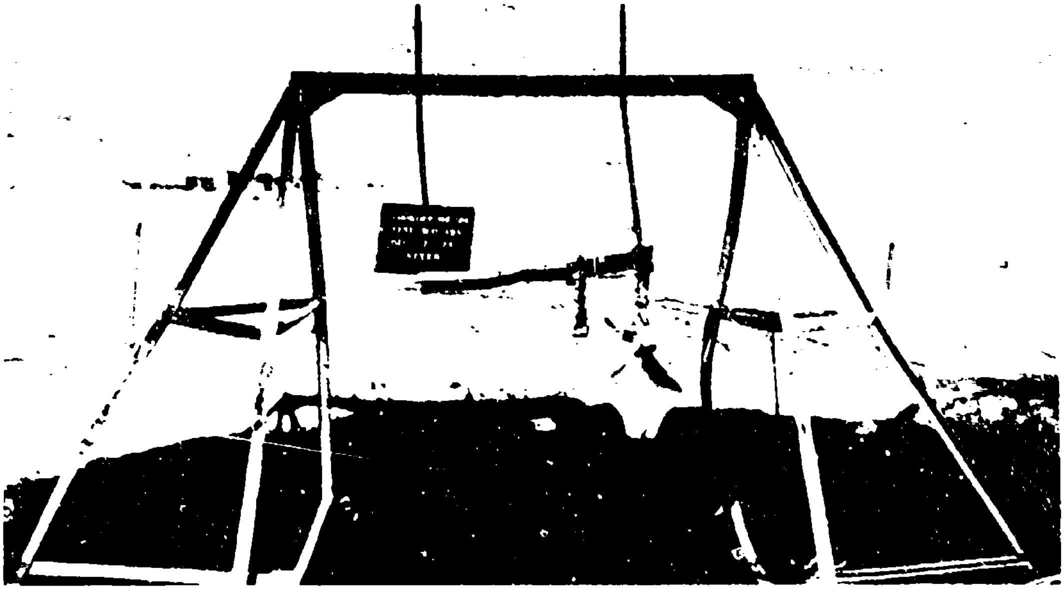

FIGURE 13. Post-Test View, SCO-125. (Neg. LHL 179887)

FIGURE 14. Post-Test View, SCO-126. (Neg. LHL 179893)

FIGURE 15. Warhead Case Fragments, SCO-126. (Neg. LHL 181064)

FIGURE 16. Mk 63 Zuni Warhead in Test Setup, Pre-Test, SCO-128-A. (Neg. LHL 180235)

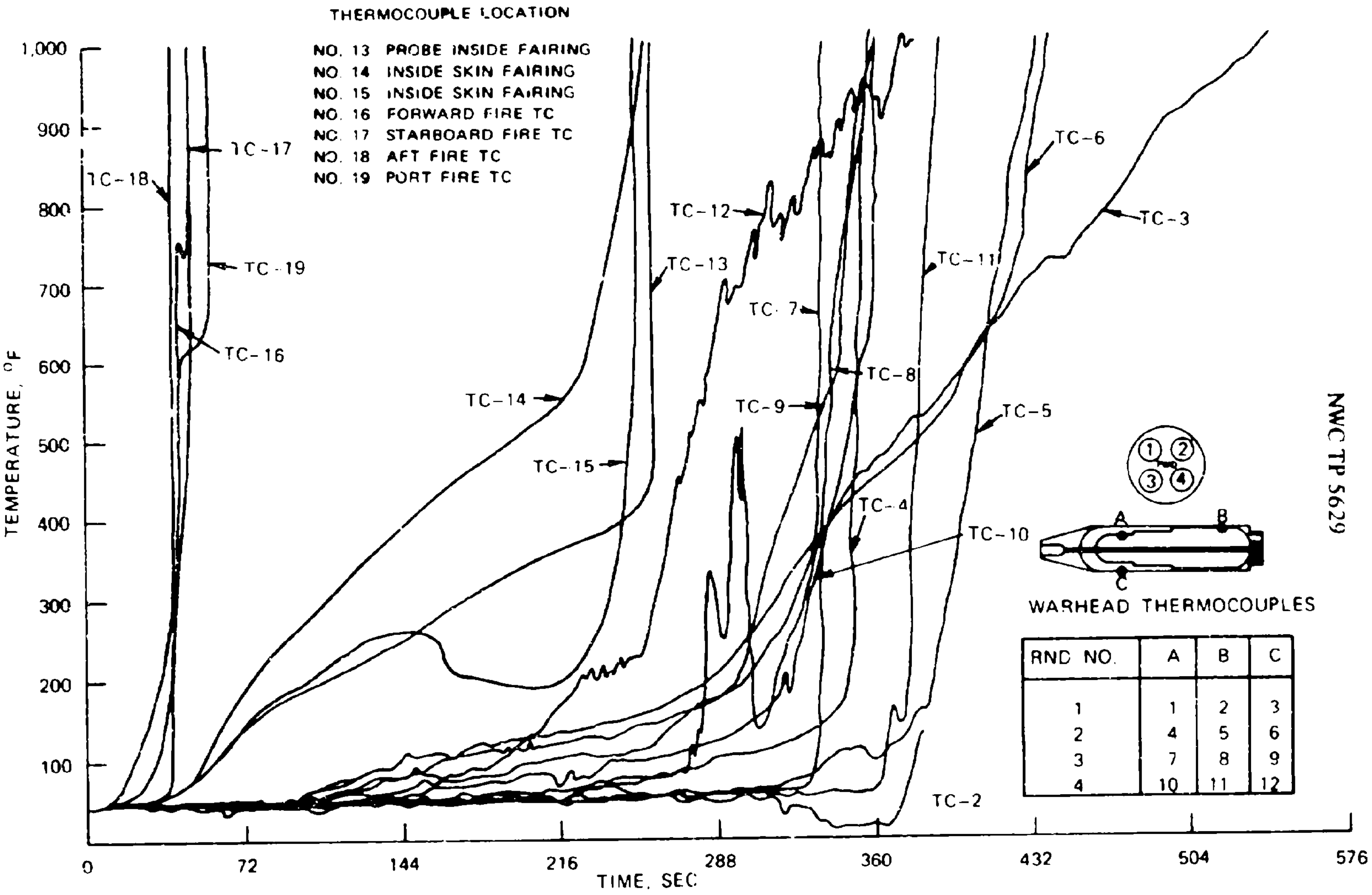

FIGURE 17. Time-Temperature Data, SCO-128-A.

in that at some point after about 4 minutes 30 seconds, the launcher evidently fell into the fire cutting off all the interior thermocouples. That is, at some time after 270 seconds, all of the thermocouples show flame temperatures.

The firing officer reported that flame covered the pit at 40 seconds (flame thermocouples 16 through 19 passed 538°C at 36 seconds). At 3 minutes 20 seconds, crackling noises (continuous) were heard (fairing thermocouples 13 through 15 rose rapidly to flame temperature as the aluminum fairing melted or burned away). Between here and 7 minutes, all thermocouples were cut off. At 8 minutes 40 seconds, jetting noises were heard and there was a report (no flash) with some flame disturbance at 8 minutes 57 seconds. Another report and a flash at the forward end occurred at 9 minutes 19 seconds with two more reports (and flash) occurring at 10 minutes 56 seconds and 11 minutes 4 seconds, respectively. On reviewing the film records, none of these events is discernable in the fuel fire flame. Fire fighting personnel could have been working at the edge of the pit with no danger to them at any time.

Post-test observations were as follows. The launcher remained on the deck with all aluminum components consumed and/or melted (Figure 18). There was no evidence of any reaction having occurred while the dummy fuzes were still on the warhead; all the dummy fuzes were on the deck at the forward end of the launcher. The remains of two warheads were still attached to transfer tubes with cubes still in place. There was no evidence of any violent reaction and all of the explosive was consumed.

Test SCO-155

During a previous wood fire cook-off test, a 250-pound Mk 81 general purpose bomb, loaded with PBXC-116 explosive, was ejected. This bomb had been instrumented with four thermocouples welded to the inside skin of the bomb at ¼ and ¾ the length of the bomb and 45 degrees each way from the strong-back. It had been exposed to a temperature of 71°C (160°F), as measured on the inside skin of the bomb, for a period of about 2 hours. This same bomb was used for test SCO-155.

For this test, the bomb was suspended by the lift rings on chains so that the interior thermocouples were located in the upper quadrants of the bomb. The standard 24-foot octagonal fire pit (1200 gallons JP-5 fuel) was used. The usual film, data logger, and closed-circuit television monitor systems were used. Figure 19 is a photograph of the test.

The time-temperature records for this test are reproduced in Figure 20. With a borderline wind velocity of 5-10 knots, the fire built up slowly and covered the pit at about 60 seconds. At 2 minutes 26 seconds, a high flare occurred with a good "*whoosh*" of noise. Burning fuel was splashed out of the pit. The bomb base ring was observed to roll slowly up out of the pit and come to rest leaning against one of the stakes anchoring the plastic pit liner (see Figure 21). This probably occurred as a

FIGURE 18. Post-Test View, SCO-128-A. (Neg. LHL 180234)

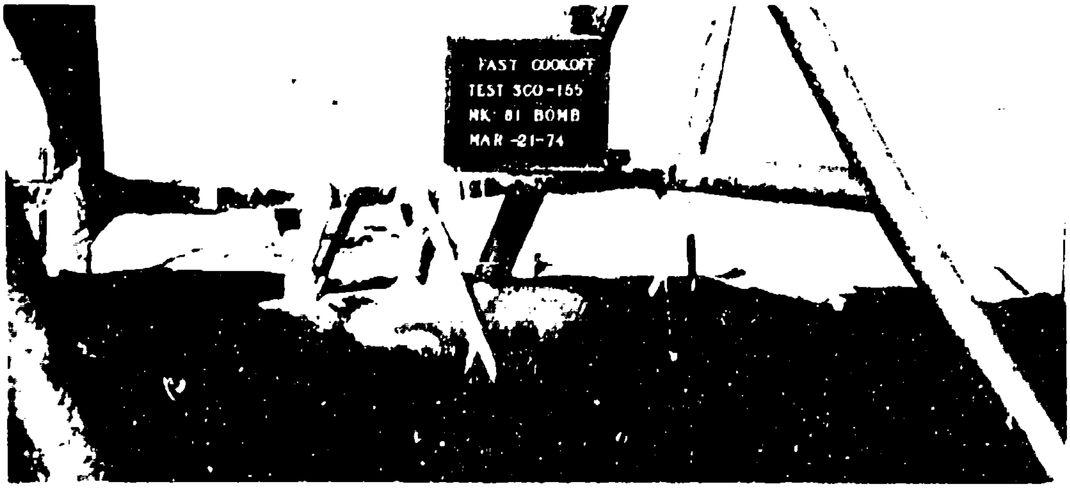

FIGURE 19. Pre-Test View, SCO-155. (LHL 182250)

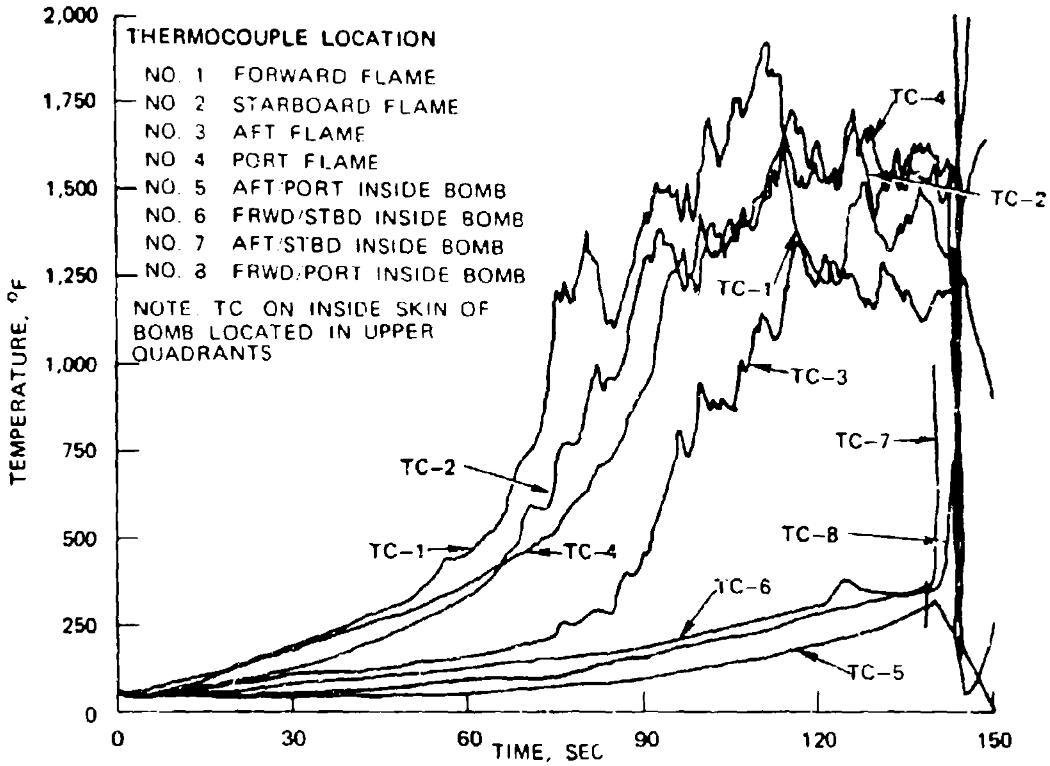

FIGURE 20. Time-Temperature Data, SCO-155.

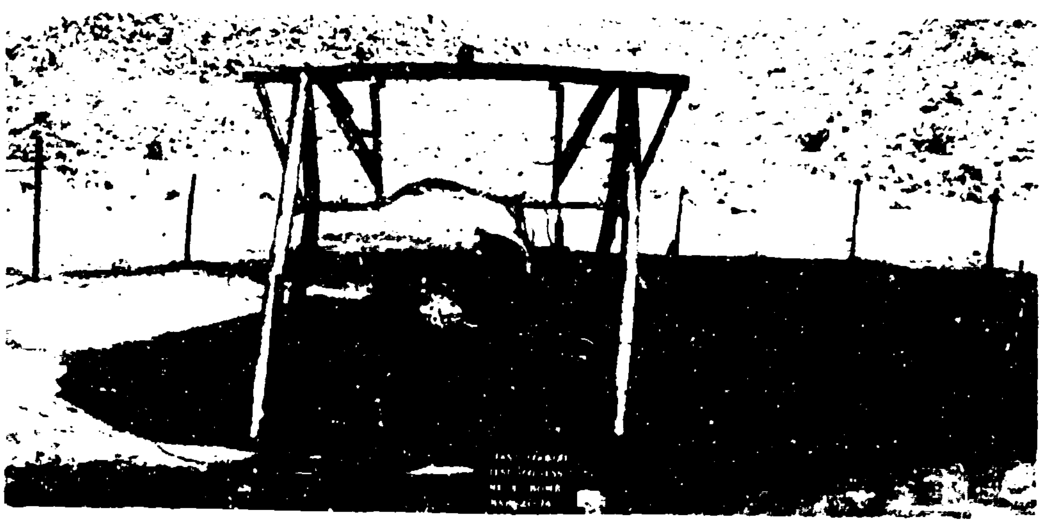

FIGURE 21. Post-Test View, SCO-155. (Neg. LHL 182248)

result of the bomb case opening and allowing the 100-pound block of PBXC-116 to fall into the flame, splashing hot fuel to make the flare. Here again, properly equipped fire fighting personnel would have been in little danger.

WOOD FIRE TESTS

A series of wood fire cook-off tests to simulate railcar fires included, among others, experiments with Tritonal as well as PBXC-116 loaded bombs. The tests consisted of a pallet of Mk 81 general purpose bombs with four live bombs and eight sand-filled inert bombs on a wood floor made up of 3- by 6-inch tongue-and-groove boards. Figure 22 is a photograph of the setup. With Tritonal filled bombs, the sequence of events was:

1. floor ignition at about 1 hour 30 minutes,

2. wood fire warmed bombs for 40 minutes, at which point

3. one bomb opened and dumped molten Tritonal into the fire, and

4. the wood and Tritonal burned for 12 minutes (Figure 23) at which point the bomb detonated initiating two other live bombs (Figure 24).

Inert bombs and fragments of inert bombs were thrown as far as one-quarter mile. The site was completely cleared, including a 10-ton steel fragment shield which was flipped over and moved 40 feet (Figure 25). In contrast, the same experiment with PBXC-116 loaded bombs, in much the same time scale, resulted in the test fixture breaking up and collapsing into one pile (Figure 26). The one live bomb that had been dropped off the pallet during the first reaction, was the one used in the SCO-155 fuel fire cook-off. These results indicate that PBXC-116 loaded bombs will be much safer for rail shipment. Thus, the danger, and the possibility of disasters such as occurred at Roseville, California will be minimized.

CONCLUSION AND RECOMMENDATION

The explosive compositions PBXC-116 and PBXC-117 have outstanding thermal, mechanical and explosive properties. The behavior of the systems in fuel fires, both the fast hot JP-5 and the slower wood fires, was a deflagration that would have caused little difficulty for fire-fighting personnel. This, along with the detonation properties and resistance to high energy impact reported elsewhere, suggests that these compositions are a real breakthrough in explosive composition development.

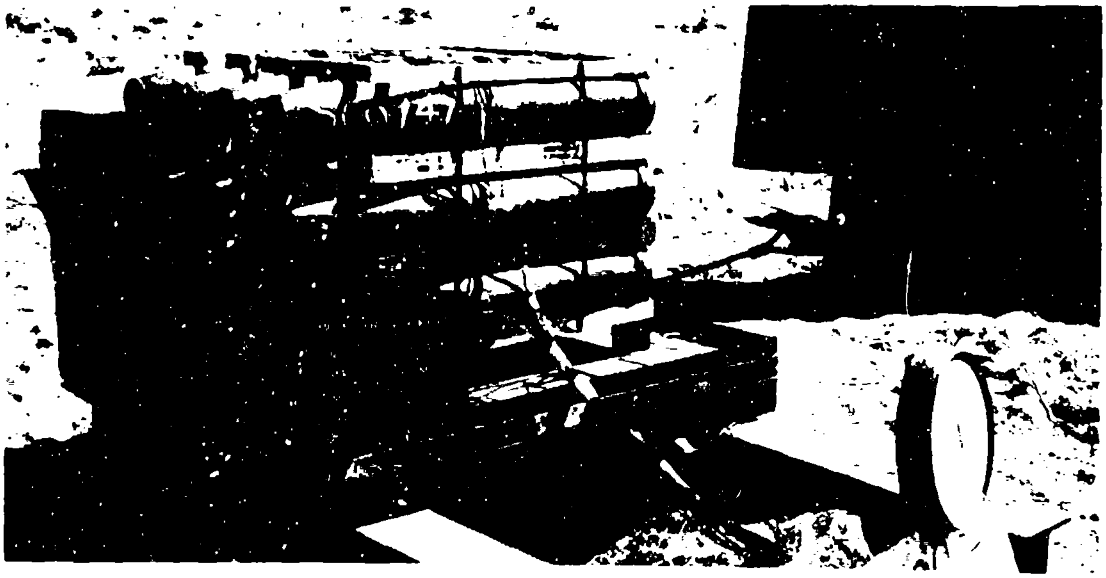

FIGURE 22. Mk 81 Bomb Boxcar Cook-Off, Pre-Test View. (Neg. LHL 182241)

FIGURE 23. Mk 81 Bomb Boxcar Cook-Off, Fire. (Neg. LHL 181904)

FIGURE 24. Mk 81 Bomb Boxcar Cook-Off, Detonation. (Neg. LHL 181901)

FIGURE 25. Mk 81 Bomb Boxcar Cook-Off, Post-Test View of Test Site. (Neg. LHL 179640)

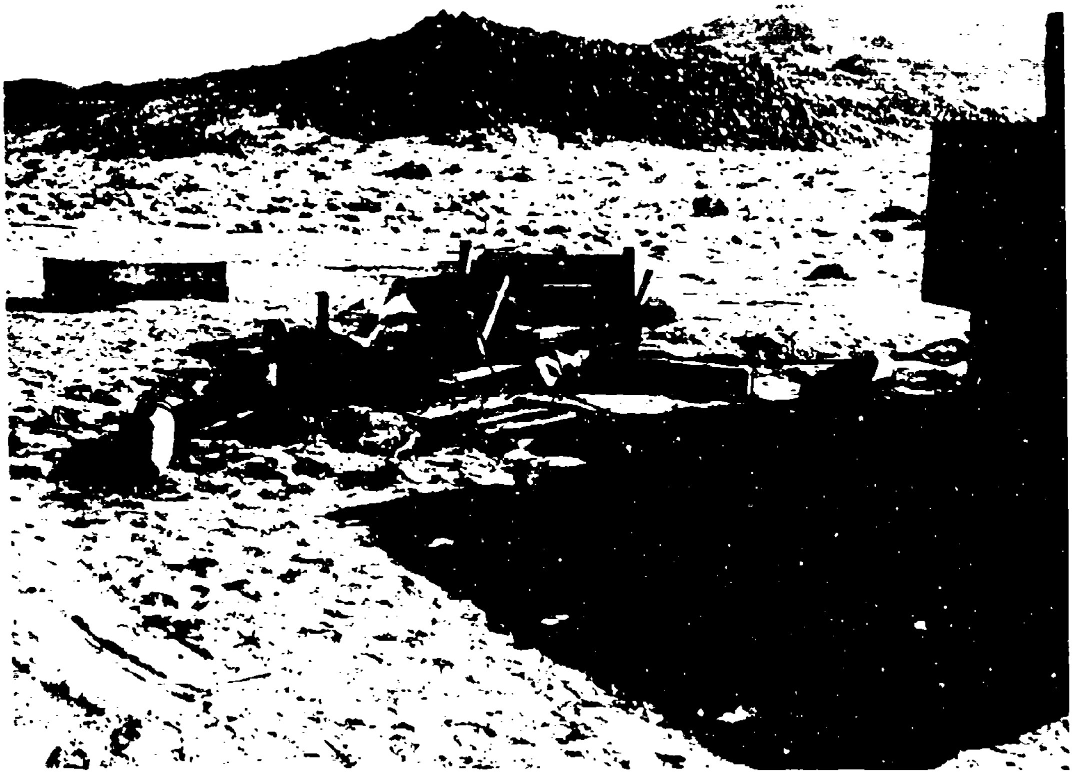

FIGURE 26. PBXC-116 Loaded Bombs Boxcar Cook-Off, Post-Test View of Test Site. (Neg. LHL 182244)

Potential applications for these explosives are many, including all carrier-based weaponry. Among the possible uses for these systems are:

1. Ordnance carried on aircraft exposed to gun fire and/or shrapnel.

2. Ordnance carried or stored in fire hazardous locations.

3. Main charge in penetration warheads or missiles where resistance to impact forces would be essential.

4. Ordnance subjected to excessive vibration and mechanical shock in shipment and storage. (A brittle composition could crack under these conditions with a resultant enhanced sensitivity and impared performance.)

5. Projectiles subjected to set-back forces which could cause premature initiation.

6. Ordnance exposed to aerodynamic heating, as on high speed aircraft where, for example, a temperature of 80°C or greater would melt a TNT-based explosive causing extrusion problems.

It is strongly recommended that these compositions, PBXC-116 and PBXC-117, be qualified in all carrier-based weapons and ordnance, in particular, when any new weapon is considered and when an old system is modified.

Appendix A

PROGRAM TO CALCULATE TIME ZERO FOR SLOW COOK-OFF

A program for the Hewlett-Packard Model 9820A calculator solves Eq. (5) and sums the fraction reacted in each 10°C interval below the furnace "*cross over*" temperature. The time required for the same fraction to react at the furnace temperature is calculated and subtracted from the "*cross over*" time to give the required equivalent time zero. The needed Arrhenius reaction rate constants must be obtained from other experimental data.

The program list is as follows:

```
0: PRT "CALC TIME 0 FOR COOK OFF"; PRT "RUN NO. SCO" ENT Z; FXD O;
      PRT Z; FLT 9; SPC 1; ENT A, B
1: O→ X→Y; ENT C,RO, R1, R2, R3, R4, R5
2: Y+3600A(RX-R(X+1))EXP(-B/1.987/((C+269.5))→Y
3: IF X≤4; X+1→X; C-10→C; GO TO -1
4: PRT "F", Y; PRT "TO", (3600 RO-Y/A/EXP(-B/1.987/C+323.2)))/3600;
      PRT "1/T1"
5: PRT 1/(C+323.2); SPC 1; GO TO 4
6: END
```

Input data for this program is: (The "RUN PROGRAM" key is pressed after each input item.)

Z = Run No.
A = Arrhenius frequency factor
B = E*, Arrhenius activation energy
C = "Cross over," oven temperature, °C
RO = "Cross over" time, hours and decimal fractions
R1 = Time at C−10°
R2 = Time at C−20°
R3 = Time at C−30°
R4 = Time at C−40°
R5 = Time at C−50°

Print out, on tape, is:
*CALC TIME O FOR RUN NO SCO "Z"
F
(total fraction reacted)
TO
(equivalent time O at furnace temperature)
1/T1 (°K)

The program then goes back to statement 1 for a second computation in the same system.

A calculator tape of this program and the results of a computation are included as Figure 27.

```
0:
PRT "CALC TIME 0
 FOR COOK OFF";
PRT "RUN NO SCO"
;ENT Z;FXD 0;
PRT Z;FLT 9;SPC
1;ENT A,B⊢
1:
0→X→Y;ENT C,R0,R
1,R2,R3,R4,R5⊢
2:
Y+3600A(RX-R(X+1
))EXP (-B/1.987/
(C+269.5))→Y⊢
3:
IF X≤4;X+1→X;C-1
0→C;GTO -1⊢
4:
PRT "F",Y;PRT "T
O",(3600R0-Y/A/
EXP (-B/1.987/(C
+323.2)))/3600;
PRT "1/T1"⊢
5:
PRT 1/(C+323.2);
SPC 1;GTO -4⊢
6:
END ⊢
R120
```

```
CALC TIME 0 FOR
RUN NO SCO
                177

F
 2.341009042E-01
TO
 4.414982122E 00
1/T1
 2.374169041E-03
```

FIGURE 27. Calculator Program Tape, Time Zero for Slow Cook-Off.

Appendix B

PROGRAM TO CALCULATE CHARACTERISTIC "CRITICAL" TEMPERATURE

This program, for the Hewlett-Packard 9820A calculator, solves Eq. (6) to determine the characteristic "critical temperature" of an explosive or propellant.

$$T_m = \frac{E^*}{2.303R\ log\left(\frac{a^2\ AQE\rho}{\lambda R T_m^2 \delta}\right)} \tag{6}$$

The equation solved is for T_m by a rapidly converging iteration from an estimated value of T_m. The program is:

```
0: PRT "ITERATE FOR T(M);SPEC 1; PRT "SAMPLE IS"; STP
1: SPC 1;ENT  RO,R1,R2,R3,R4,R5,R6,R7,R8
2: PRT "E",RO,"A",R1,"Q",R2,"LAMBDA",R3,"RHO",R4,"C",R5,"DEL"
3: PRT "R",R7;SPC 1;PRT R8;SPC 1
4: ENT A;PRT A;A+273.16→ X;ENT B; PRT B;BB→ A;SPC 1
5: RO/R8R7LOG (AR2R1R0R4/R3R7XXR6)→X
6: PRT X-273.16;IF ABS (Y-X)≤ 1E-2; SPC 1;GTO +21
7: X→Y;GTO  2
8: PRT 1/X;PRT "TAU",AR4R5/R3;1/(1/X-1.6/R0)-273.16→Z;PRT
   "T1",Z;SPC 2;GTO -4
9: END
```

Input data for this program is (Note: At the STOP after printing "SAMPLE IS," press PRINT, ", SAMPLE INDENT, ", and EXECUTE.):

R0, E^* = Arrhenius activation energy, cal/mole
R1, A = Arrhenius frequency factor, sec^{-1}
R2, Q = Heat of reaction, cal/g
R3, λ = Thermal conductivity
R4, ρ = Density
R5, c = Specific heat
R6, δ = Shape factor
R7, R = 1.987 cal/mole-°K
R8, 2.303
A T_m, estimate
B a = radius or half thickness

The RUN PROGRAM key is pressed after each item entered. The program prints out the input values followed by the T_m iteration values. The program then prints $1/T$

(°K), the value of $\tau = a^2\rho c/\delta$ for the sample size, and the value of T_f for $t_e = \tau$. The program then returns to statement 3 to repeat the computation at a new size.

Any of the input parameters may be changed by pressing STOP twice and CLEAR. The new values are added by entering the number followed by →, R and the appropriate number from the input list. Pressing GO TO, 1, EXECUTE, and RUN PROGRAM initiates the new problem.

An example of the calculation is given in Figure 28.

```
0:
PRT "ITERATE FOR
 T(M)";SPC 1;
PRT "SAMPLE IS";
STP ⊢
1:
SPC 1;ENT R0,R1,
R2,R3,R4,R5,R6,R
7,R8⊢
2:
PRT "E",R0,"A",R
1,"Q",R2,"LAMBDA
",R3,"RHO",R4,"C
",R5,"DEL",R6⊢
3:
PRT "R",R7;SPC 1
;PRT R8;SPC 1⊢
4:
ENT A;PRT A;A+27
3.16→X;ENT B;
PRT B;2B→A;SPC 1
⊢
5:
R0/R8R7LOG (AR2R
1R0R4/R3R7XXR6)→
X⊢
6:
PRT X-273.16;IF
ABS (Y-X)<1E-2;
SPC 1;GTO +2⊢
7:
X→Y;GTO -3⊢
8:
PRT 1/X;PRT "TAU
",AR4R5/R1...(1/
X-1.6/R0)-273.16
→Z;PRT "T1",Z;
SPC 2;GTO -4⊢
9:
END ⊢
R105
```

```
ITERATE FOR T(M)

SAMPLE IS
AFX-301

E
 3.260000000E 04
A
 2.800000000E 11
Q
 3.000000000E 02
LAMBDA
 2.000000000E-04
RHO
 1.300000000E 00
C
 3.800000000E 00
DEL
 2.000000000E 00
R
 1.987000000E 00

 2.303000000E 00

 1.000000000E 02
 2.540000000E 00

 1.382280216E 02
 1.402503789E 02
 1.403525904E 02
 1.403577443E 02

 2.418275912E-03
TAU
 1.593545200E 05
T1
 1.405248683E 02
```

FIGURE 28. Calculator Program Tape, Characteristic "Critical" Temperature.

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101 Chemical Propulsion Mailing List No. 271 dated October 1975, including Categories 1,2,3,4,5

AD-A026 525

ERRATA

Footnote 2 on page 3 is incorrect.

Please make the following change:

[2]Naval Ordnance Systems Command. "Interim Qualification of PBXC-116(I) Explosive Composition", 9 April 1974, and "Interim Qualification of PBXC-117(I) Explosive Composition", 11 April 1974. Washington, D.C., NAVORD-0332A. (NAVORDNOTICE 8020. publication UNCLASSIFIED.)